MENCH & LAGERSTROM

Investigation of Alternator

Electrical Engineering

B. S.

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INVESTIGATION OF ALTERNATOR

BY

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

John George Mench and David Reuben Lagerstrom

ENTITLED Investigation of Alternator

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

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TABLE OF CONTENTS.

PLATES.

TABLES.

INVESTIGATION OF ALTERNATOR.

I. INTRODUCTION.

In the operation of alternating current apparatus, many phenomena are encountered that are more or less elusive, and it becomes necessary for the investigator to make certain assumptions in the solution of the problem at hand. Likewise in the application of formulae that he has deduced, he must estimate the value of constants or ratios involved. This he does as conservatively as possible, but it is desirable that he be able to test the validity of the assumptions made, by experiment , and it is with such a test in mind that this thesis has been attempted.

II. THEORY.

If two alternators, synchronized and generating equal electromotive forces, are driven at such speed with respect to each other that neither is receiving or delivering power, their armatures must necessarily be in the same space relation or mechanical position. If now the driving force of one machine be removed it must fall behind the other in mechanical position far enough to receive a driving torque sufficient to keep it in synchronism and to carry it at the proper speed . This machine will thus become a motor, being supplied with power from the first machine, and may furthermore be loaded additionally to the point of breaking synchronism. As the load on the motor is increased the angular displacement of the motor armature also increases, thus giving the larger torque necessary to carry the greater load.

If the driving torque of the machine under discussion had been increased, instead of decreased, the motor would have become a generator and would have furnished power to the other machine running it as a motor. By virtue of the same reasoning as above, the armature of the machine supplying the power must take up a position ahead of the no-load position and lead the other armature, to be able to exert any pulling force upon it. Also this displacement must increase with increase of load or power supplied, being just the converse of the first case.

This angular displacement is indeed a variable quantity depending obviously upon the load and the individual machine as well as on the type of machine, being much greater in machines of uniform magnetic reluctance than in definite pole machines. That the displacement would be less in the case mentioned would be expected, since the pole piece covers but 50 to 70 percent of the pole pitch,

which means that the field flux will be crowded into one of the pole tips much more densely with a slight shift of the armature than in the other type of machine. Also the displacement will be less when the machine is running as a motor than when running as a generator, since in the latter case the compounding effect is greater for the same value of armature current. From the equations for synchronizing torque it would seem that the displacement would vary with the degree of field excitation, but such is shown by the tests made, not to be the case, i. e., the displacement remains constant for any given load regardless of the field excitation of the motor.

With machines of uniform reluctance, or "round rotor type" this angular displacement is readily shown and calculated from Figure I. Here OE_0 represents the generated e.m.f. impressed upon the terminals of the motor and Oe' represents the equal and opposite counter e.m.f. generated by the motor when the two machines are driven abreast of each other, i.e., when neither is operating as a

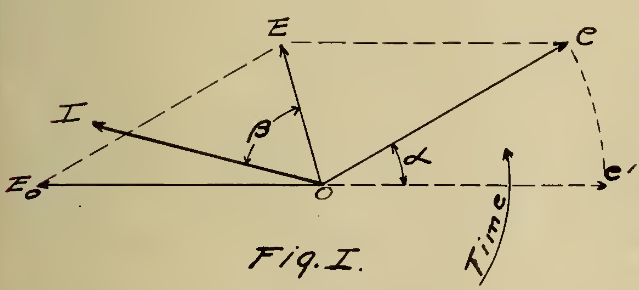


Fig. I.

motor. At this position the two e.m.f's are 180° apart, and since the resultant is zero no current will flow from one to the other. This condition does not always obtain in practice due to slight surges which cause a small current to flow, but is theoretically true. When the driving of the motor is cut-off--the machines having been synchronized -- its armature will fall back by an angle, say α, which will swing the counter e.m.f. through the same angle to the position of Oe as shown in the figure. This will give a resultant, OE, which must then be consumed as impedance drop by the resultant

current OI flowing. This current will lag behind OE by the angle β where β is arc tan. $\frac{X}{r}$, x and r being respectively the "synchronous reactance" and the resistance of the motor. Using the counter e.m.f., of the motor Oe as reference vector, the power taken by the motor is found to be,

$$P = \frac{e}{Z}\left(e \cos\beta - E_0 \cos(\alpha - \beta)\right).$$

From the pwer taken by the motor, with the aid of the formula just cited the angle α may be calculated for any load.

In the study of definite pole machine however, this angular displacement cannot be well calculated due to the effect of armature reactions and self induction, both of which are variable depending upon the position of the active slot with respect to the poles.

Armature reactions represents the m.m.f. of the armature currents, and in a single phase machine varies between zero and $\sqrt{2}NI$ where I is the effective current in the windings and N is thenumber of turns per pole, the factor $\sqrt{2}$ changing the current from effective to maximum value. For two phase machines the value of armature reactions is $\sqrt{2}$NI , and for three phase is $1.5\sqrt{2}NI$ and are of constant value, I being the effective current in the windings as before and N being the number of turns per pole per phase. This m.m.f. may have a magnetizing or demagnetizing effect, or it may simply shift the field flux in the pole piece, or it may do both. Since the energy component of current is a maximum when the effective slot is directly under a pole, its effect will be only to shift the field flux . But since the reluctance of the slot flux is not uniform all the way around the armature in a definite pole machine the amount

of this shift cannot well be predicted for any machine. The wattless compenent of current either lags behind or leads the other by 90° electrical and hence reaches its maximum when the slot is directly between the poles, producing only the magnetizing or demagnetizing effect.

The self induction of the machine is caused by flux set up by the armature currents, which flux does not interlink with the field flux . In a definite pole machine this varies with the position of the slot, being a maximum when the slot is directly under a pole, at the same time when the pwer component of current is a maximum also. The inductance is then a minimum when the slot is midway between the poles where the reluctance of the path of the leakage flux is greatest, which position corresponds to the maximum of wattless current. The maximum of self induction is found to be about 50 % greater than the minimum. With machines of uniform reluctance the self inductance is constant for all positions and hence will be the same for both energy and wattless components of current.

From the foregoing it is evident that for machines of uniform reluctance it is possible to show diagrammatically the internal reactions. But with the definite pole machines this cannot be done and the subject must be studied analytically as in the following development.

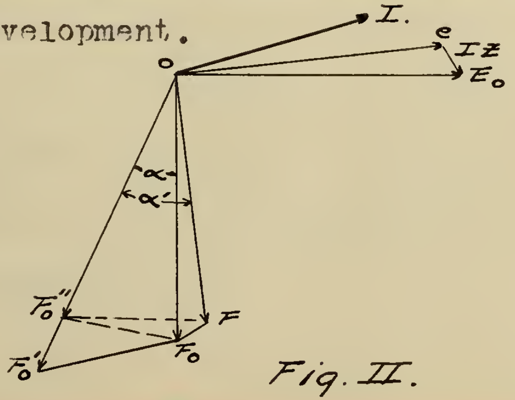


Fig. II.

If Oe Figure II represents the terminal e.m.f. of a generator the total induced e.m.f. E_0 must be generated when the current I is flowing due to the selfinductive impedance drop IZ, which is added to e vectorially. If OF_1 represents the m.m.f. necessary to give the flux for generating e, then OF_0 will be required for E_0. If there were no distorting or demognetizing action of the armature current the field excitation necessary to set up the conditions shown would correspond to OF_0 and could be obtained from the magnetization curve directly. But due to the armature reactions a component in the direction of the current must be added to OF_0, and F_0F_0' which is the m.m.f. corresponding to the armature current and in phase with it. Thus the total field excitation necessary with the load current I flowing will be OF_0' , and the armature will have been displaced mechanically through the angle α' . Due to the fact that the data in this test was taken for single phase, in which case the armature reactions are pulsating, the impedance drop-- and consequently the small angle ($\alpha' - \alpha$) has been neglected, making e and E_0 coincident in the figure. This results in making F_1F_0'' represent the armature reactions, which assumes the armature current appear more nearly in phase than is actually true. However the above assumptious may well be made without appreciable error since the small angle ($\alpha' - \alpha$) is within the limits of accuracy of measuring the angular displacement in the test.

Now for the sake of deriving a formula for the angular displacement, the original discussion will be continued, assuming the following notation:--

e_0 = induced e.m.f. per phase.

e = terminal e.m.f. per phase.

F_0 = m.m.f. from saturation curve corresponding to e_0 .

$I = i + ji_1$ = armature current per phase.

$Z = r - jx$ = self inductive impedance per phase.

F = no load field excitation from saturation curve corresponding to e.

Then, $E = e + IZ = e + (\ i - ji\ )(r - jx) =$

$$e + ir + i_1x - j(ix - i_1r).$$

This gives in complex quantities the induced e.m.f. in machines of uniform reluctance.

For definite pole machines the formula becomes, when modified in accordance with the previous discussion on page #5,

$E_0 = e + ir + i_1x - j(1.5ix - i_1r)$ where x, the self inductive reactance is taken as 50% greater for energy component of current than for wattless component.

The m.m.f. N corresponding to the real part of the expression, $(e + ir + i_1x)$ is obtained directly from the saturation curve. The m.m.f. N_1 corresponding to the imaginary part of the expression, $(1.5ix - i_1r)$ is taken by proportion from the tangent to the saturation curve at the value of N as shown in figure III. (From "Electrical Energy" by Dr. E. J. Berg.)

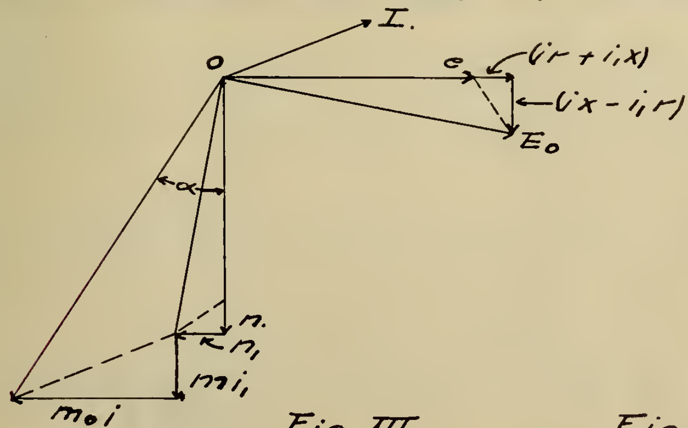


Fig. III.

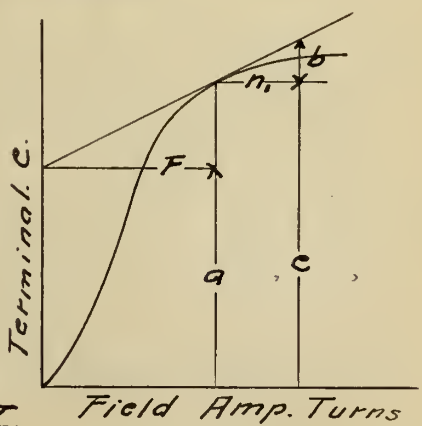


Fig. IV.

If b is the e.m.f. corresponding to the imaginary component of E_o and a the ordinate of the point of intersection of the tangent with the E - axis, then, $\frac{b}{n_1} = \frac{e - a}{F}$, or solving the proportion, $n_1 = \frac{Fb}{e-a.}$

Since the flux or m.m.f. is 90^0 ahead of the e.m.f. that it induces, the two components may be represented by $(-n_1 - jn)$ as shown in figure III. The armature m.m.f. will likewise have two components and will be equal to

$$m(i + ji_1) = mi + mji_1 = m_oi + jmi_1)$$

where $M = \sqrt{2}N$ for two phase and $1.5\sqrt{2}NI$ for three phase as mentioned on page # 4, and where M_o = Km, K being some constant. The value of K has generally been assumed as .5 but the opinion stands that a larger value should be used and it is an object of this thesis to determine a better value. Combining the two above mentioned m.m.f.'s the equation becomes,

$-n_1 - jn = m_oi + jmi_1 - F$ or $F = M_oi + n_1 + j (mi_1 + n)$.

The quantities in this equation are shown in their proper phase relation in figure III, which is a slightly modified form of figure II. In this equation, $M_o = m$ and the value of x is the same for both components of current in machines of uniform reluctance, but in definite pole machines the restrictions previously noted for m_o and x must be observed. From figure III it is seen that the angular displacement α, is arc tan $\frac{m_oi + n_1}{mi_1 + n}$ for definite pole machines and is arc tan $\frac{mi + n_1}{mi_1 + n}$ for round rotor machines, the algebraic signs of the currents being taken as positive where the machine is run as a generator and negative

when running as a motor . The displacement will of course be less in the case of motor, which is born out by the test in this paper.

III. TEST.

APPARATUS.

The machine used was a General Electric 4 pole Rotary Converter #28366 of the following specifications:--

7.5 KW. , 68 amp. 110-160 volts.

Number of slots = 48, size .304" by .94".

Number of commutation segments, 96.

Speed , 1200 - 1600 R. P. M.

Armature winding - 4 circuit, 96 coils, 3 turns per coil of #10 B & S., D. C. C.

Total number of conductors, 576; 144 in series per circuit.

Field winding shunt, resistance, 47.4 ohms @ 20°C

1725 turns per pole of #17 B.& S., D. C. C. Total = 6900 turns. The machine was used as an alternator only, the brushes having been lifted from the commutator on the D. C. side.

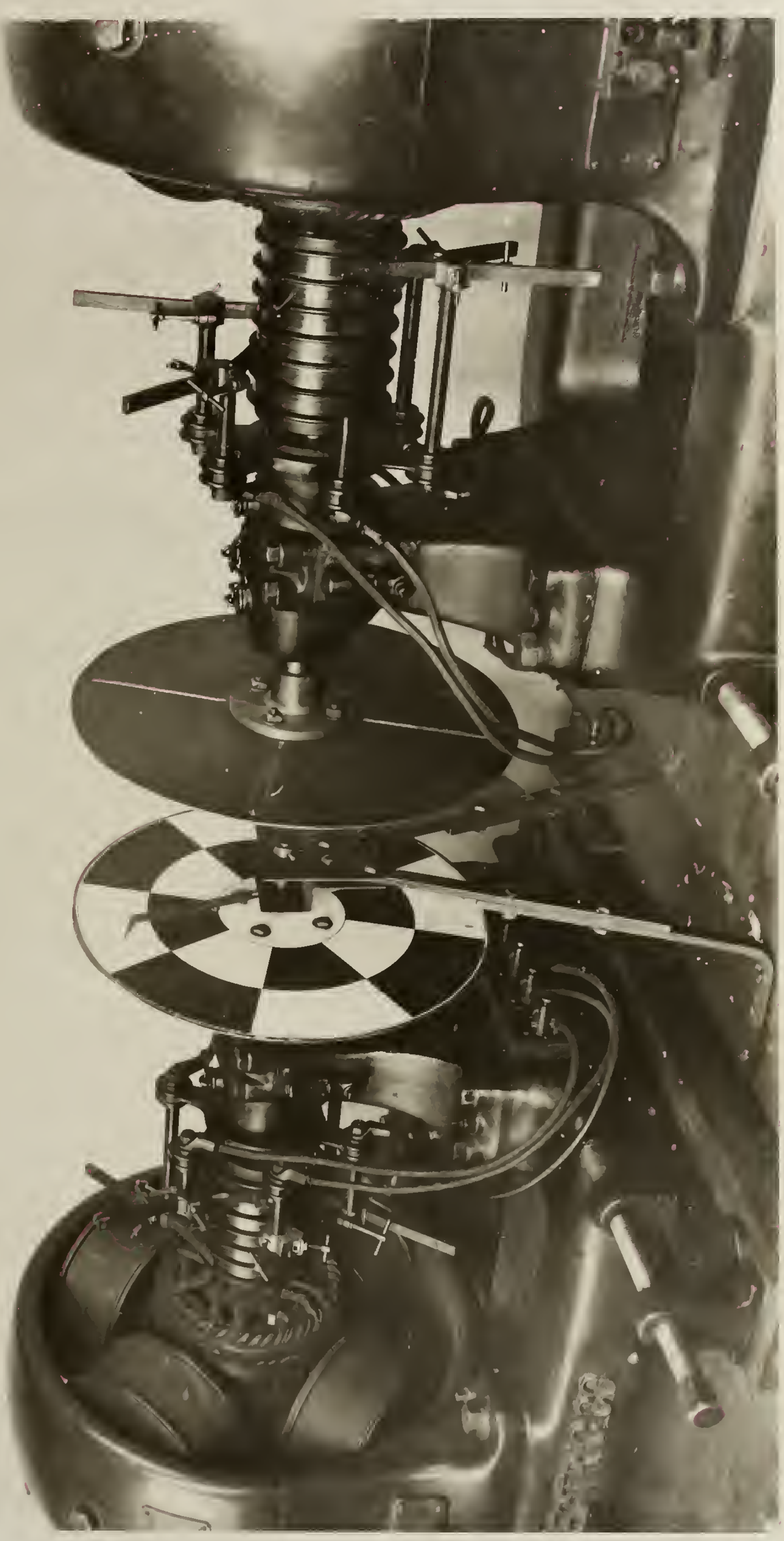
The apparatus used in measuring the angular displacement of the armature under study was designed and constructed by the authors, and is shown as assembled on the machines in the accompanying photographs. A large steel disc 1-16" thick and 18" in diameter is attached to the shaft of the machine studied having cemented upon its face a heavy white paper cover with two sets of four black sectors. A similar steel disc with four radial slots at right angles to each other and 1-8" wide is attached

to a similar machine used as the reference machine. This disc was designed with a safety factor of ten, neglecting the metal left at the outer end of the slots. The two machines are so placed that their shafts are exactly in line and a short piece of smaller shaft is mounted between them in the supports shown. One end of the shaft carries a pointer directly in front of the disc and the other an index moving over the graduated scale also mounted on the supports . The index may be clamped at any position on the shaft permitting the use of any part of the scale, and the pointer is made extensible so that measurements may be taken on either set of sectors. An arc lamp with condensing lenses is placed back of the reference machine, the light being projected between the two upper field poles of the reference machine, and throughthe slots upon the sectored disc.

When the machines are running in opposite directions the narrow bands of light passing through the slots sweep over the sectors, and if the two speeds are equal these sectors will appear to be stationary and half their actual width. If the two speeds are not equal, the sectors will appear to rotate at a speed equal to half the difference of the machine speeds.As said before, if the two speeds are equal, which obtains when the machines are synchronized, the sectors appear to be stationary and the pointer may be set at one edge of any particular sector. The figure V, OA represents the edge of one of the sectors when the machines are synchronized which is the line of intersection of the band of light and one of the sectors on the disc. If the motor armature __ carrying the sector disc__ be displaced by the angle α as indicated, the intersection of the light and the sector will then occur midway between A and B and the

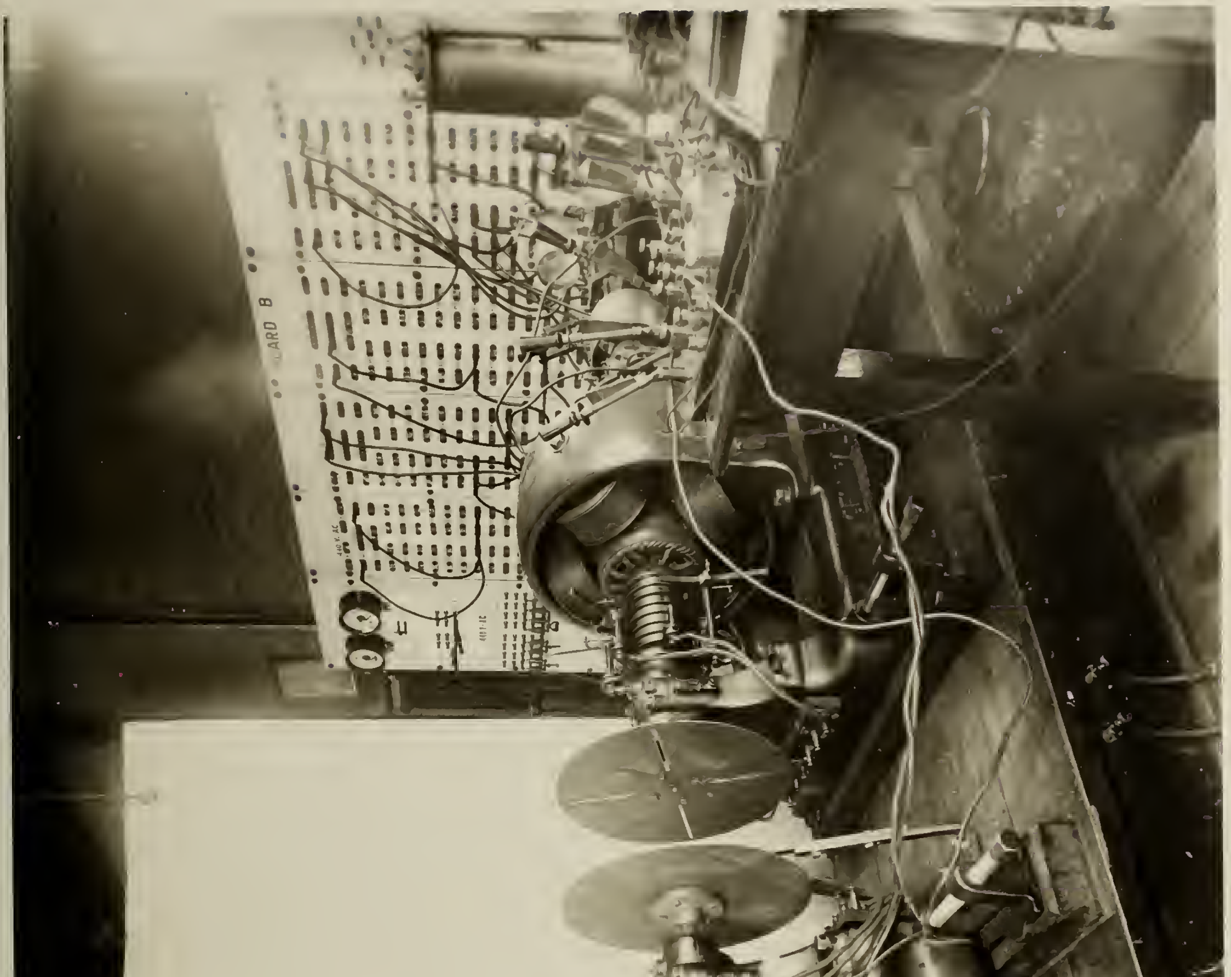
Photograph of Apparatus

Plate I



Photograph of Apparatus

Plate II



Photograph of Apparatus

Plate III

pointer will measure but half the actual displacement of the armature. This method does not become void if the generator armature should also be displaced, because the motor armature

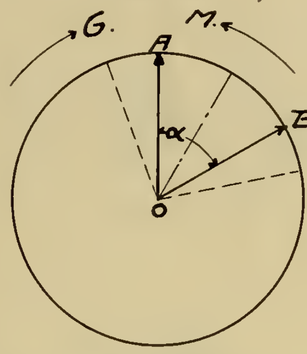


Fig. V.

would receive the same displacement in addition to that caused by the load, and the result would remain that due to load only.

METHOD OF TESTING.

In making the tests the machine carrying the slotted disc was not run as a generator but was left floating on the line unloaded with normal excitation, so that it kept in the same space position as the generator, being called for this reason the reference machine. The power used was furnished from a large motor - generator sub station set, with rheostats in both fields so that the freguency and voltage impressed upon the machine under test could be kept constant.

The reference machine was started from the D. C. side, and after synchronizing was left floating on the line. The other machine, belt driven from a shunt motor, was brought up to normal speed and excitation and also synchronized, being connected to the line through an ammeter, with a frequency

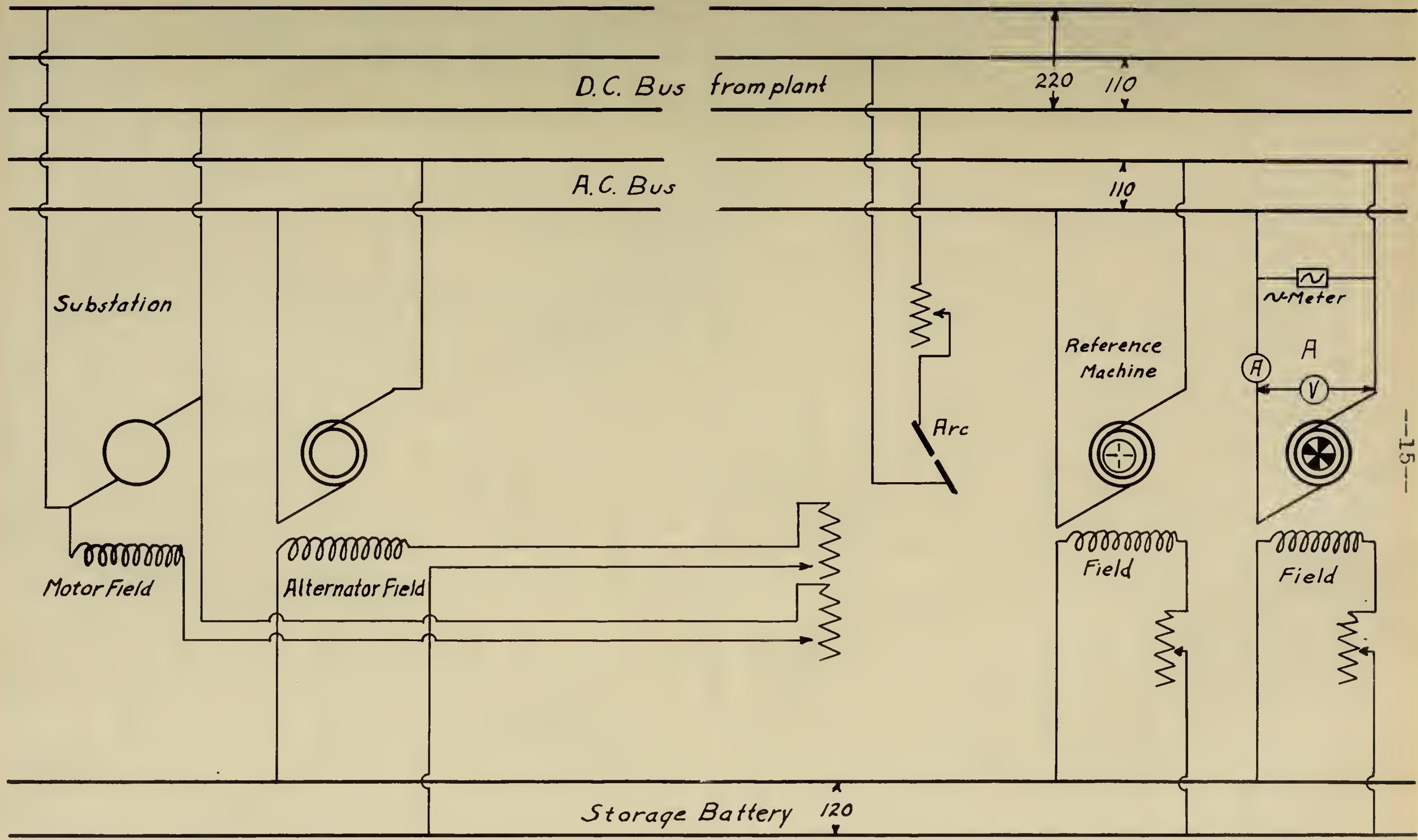


Diagram of Connections

Plate IV

meter and volt meter across the terminals. The field of the D. C. motor was so adjusted that the minimum current readings of both ammeters was obtained, the D. C. imput being noted for the friction and windage losses of the two machines. Theoretically the A. C. ammeter should read zero when the machines are thus driven abreat of each other, but it did not owing to slight surges that caused about 7.5 amperes of pulsating current to flow. The reading of the index when the pointer was set at one edge of a sector was taken at this time and called the zero reading. The driving torque of the D. C. motor was increased until the ammeter indicated that the machine was delivering power back to the substation. The reading of the index for the pointer set to the new position of the sector was taken, as was also the A. C. and D. C. current and voltage. This same set of data was continued for increasing values of torque until the full load current of the machine had been exeeeded. The driving torque was then reduced to its original value to check the zero reading of the index again. The D. C. power was then cut off and the data taken as before, the machine now operating as a motor and supplying only the friction and windage of the two motors, i. e., with no D. C. out put. The A. C. motor was then still further loaded by operating the D. C. motor as a generator loaded with lamp banks, taking the same readings for increases of load up to the value of A C. current as when the machine was operating as a generator. This set of data just described was taken with the field of the motor remaining constant. Another set was taken with the motor operating at constant load, but with the field varied from one extreme to the other, readings being taken for each value of field current. This was repeated for a second

load slightly greater than the first.

IV. CALCULATIONS.

The angular displacement corresponding to any load was obtained by subtracting the zero reading of the pointer from the reading for the corresponding load, and multiphying the difference by two. Since these readings were taken to the nearest half electrical degree, the angular displacement is obtained to the nearest whole degree only.

In working up the results, the value of the constant K or the ratio of M_0 to M was found as follows:-- Using the values of α as found from the test the diagram on plates and corresponding to figure II, were constructed, and the values of armature reaction scaled off. The values of armature reaction were then calculated for the same values of current the ratio of the scaled to the calculated being the value of the constant, K, sought. The armature reactions were calculated from the formula, Ampere turns, A.T. = 22.9N., which is in turn derived as follows:-- In single phase, armature reactions A. R. $= \sqrt{2}NI$ for maximum and zero for minimum as stated before. In this machine there are 72 turns per pole and since the winding is distributed over half the circumference of the armature this value 72 must be multiplied by $2/\pi$ the distribution factor, which is the ratio of semi-circumference to diameter. When effective current is used in the above formula, the factor $\sqrt{2}$ enters to give the maximum value of armature reactions, but since the value pulsates between zero and the value given above

and since the effective value of armature reactions is desired, the factor $\sqrt{2}$ may be omitted and the product NI used. In this expression I is the current in the windings and if I is to be taken as the line current which divides in half-- the factor one half must be inserted. Thus the value of calculated armature reactions.

$$A.\ R. = 72 \times I/2 \times 2/\pi = 22.9N.$$

where I is effective value of current in the line.

The D. C. power input for generator action is the product of D. C. E and I . The A. C. output is the D. C. input minus the losses, which are D. C. Armature I^2R , A. C. armature I^2R and the no load friction and windage losses. Conversely, when the alternator is running as a motor, the power taken from the A.C. bus is equal to the D. C. generator out put plus the above losses. With the value of the actual power as obtained thus and the product of A. C. E and I the power factor of the current taken or furnished by the alternator maybe calculated.

V. CONCLUSIONS.

As previously shown, the ratio of the scaled armature reactions to the calculated should be the value of K, the ratio of m_0 to m . In the first set of data taken, Plate VIII and Tables I and II with e and E_0 equal and constant the of K was found to be .63 for generator action and.59 for motor action, neglecting the small values of current due to unsteady conditions.

The mean of the two is .61 which indicates that the value .5 as usually assumed is somewhat low.

The data taken with variable field excitation Plate IX and Tables III is not dependable, giving valus of K greater than unity. Here the angular displacement was found to be constant for any given load, regardless of the field excitation. The great difference between the scaled and calculated values is due to the fact that when the impedance drop is neglected in the small displacement angle as shown, a very considerable error is made. If this could be taken into account the armature reaction vectors for under excitation would be drawn from points above the one shown, and below for over excitation thus reducing the values for extremes of excitation but leaving them as they are for nearly normal. As would be anticipated, the ratios obtained for the larger loads and angles in both tests are the more consistent.

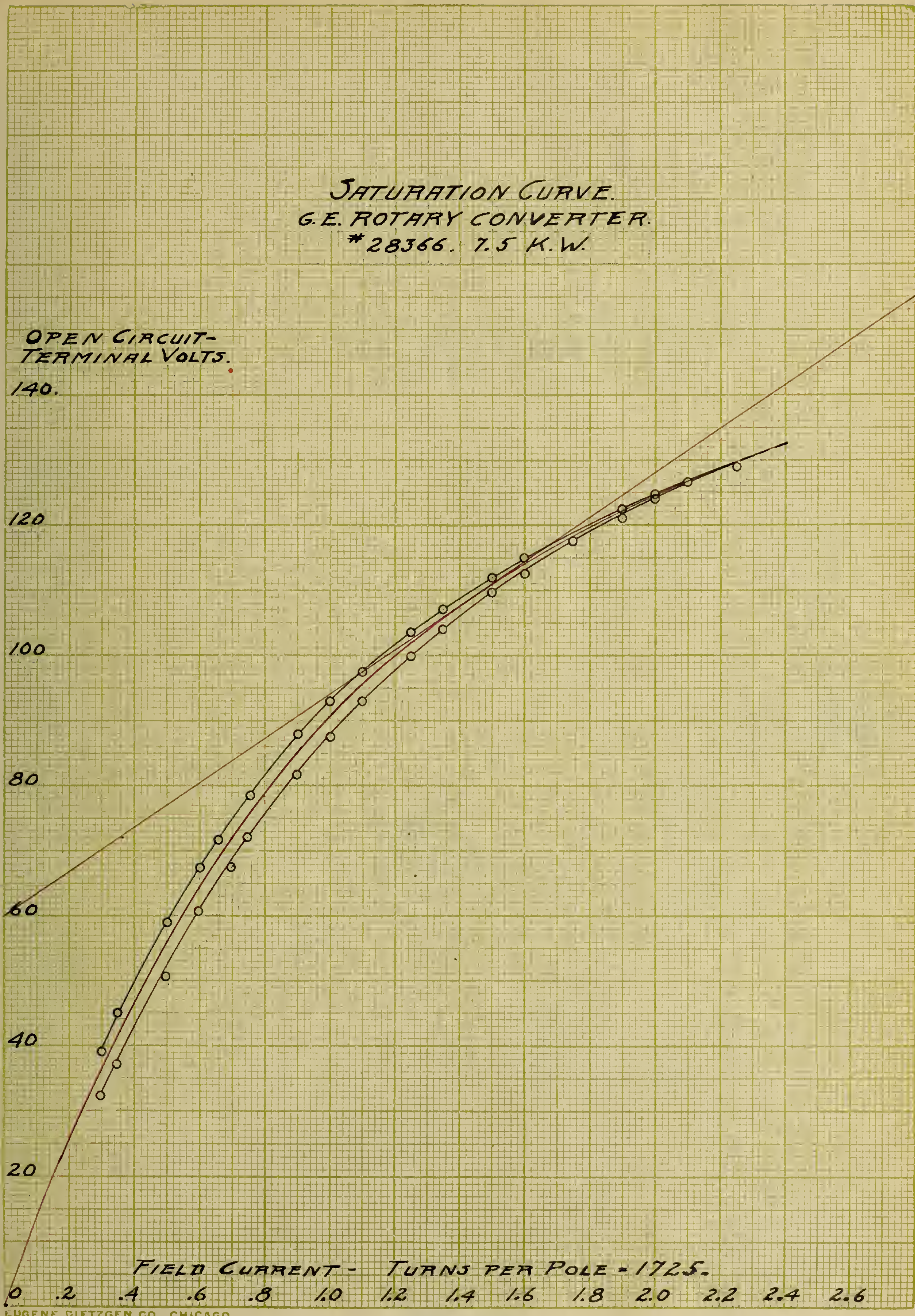

SATURATION CURVE.
G.E. ROTARY CONVERTER.
#28366. 7.5 K.W.
OPEN CIRCUIT-
TERMINAL VOLTS.
140.
120
100
80
60
40
20
FIELD CURRENT - TURNS PER POLE = 1725.
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
EUGENE DIETZGEN CO., CHICAGO.

Plate V

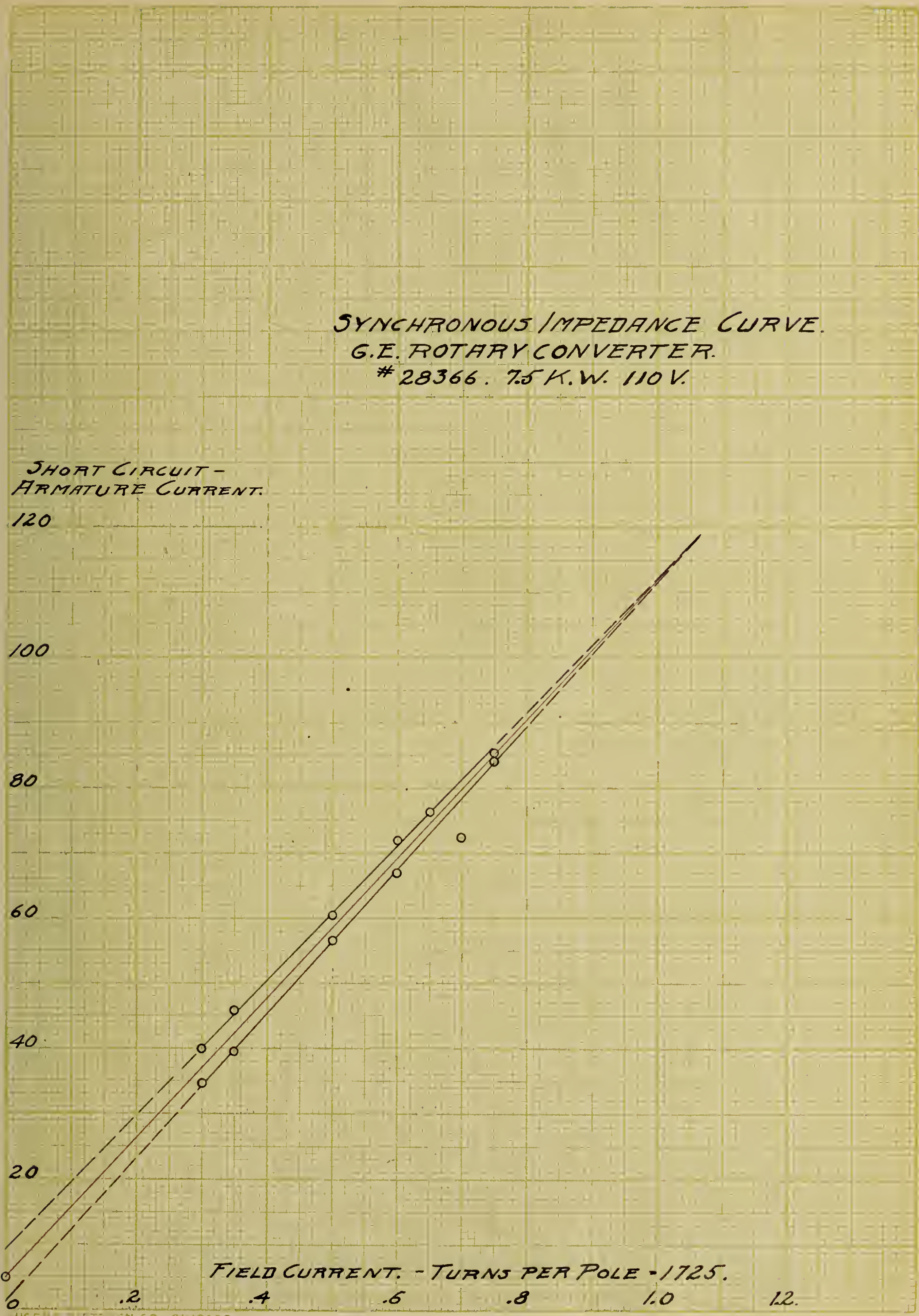

SYNCHRONOUS IMPEDANCE CURVE.
G.E. ROTARY CONVERTER.
28366. 7.5 K.W. 110 V.
SHORT CIRCUIT -
ARMATURE CURRENT.
120
100
80
60
40
20
FIELD CURRENT. - TURNS PER POLE - 1725.
0
.2
.4
.6
.8
1.0
1.2.

Plate VI

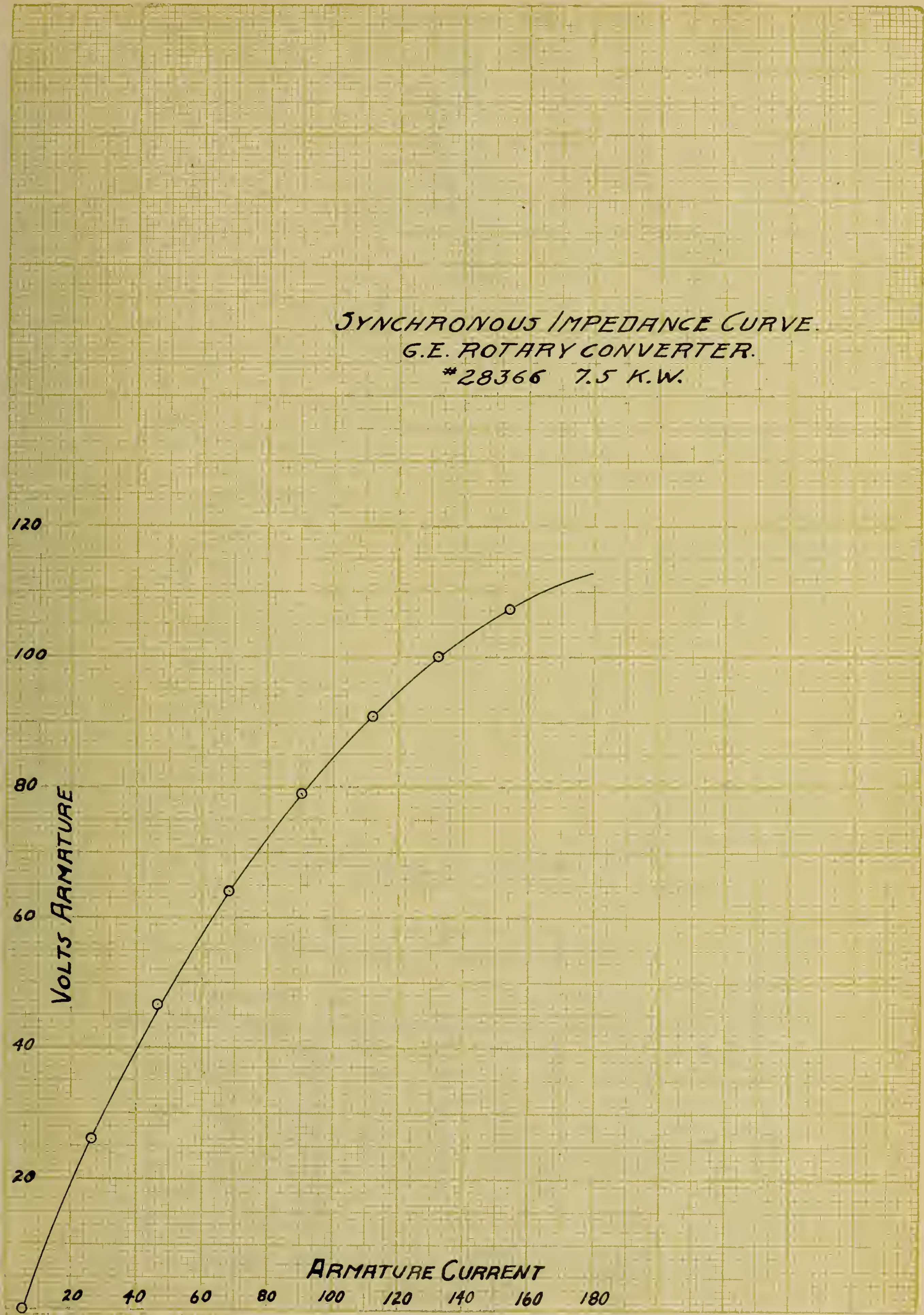
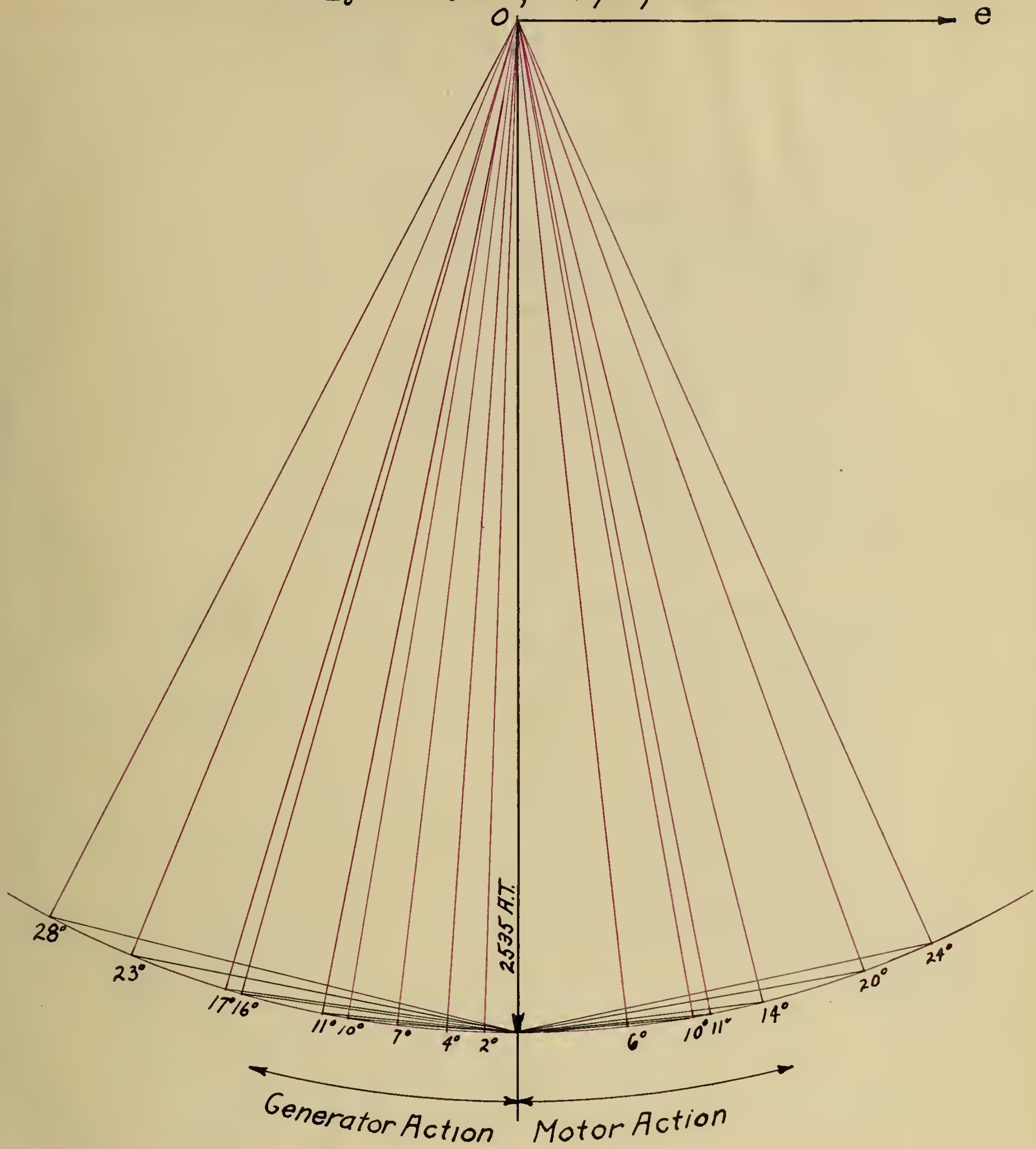

SYNCHRONOUS IMPEDANCE CURVE.
G.E. ROTARY CONVERTER.
*28366 7.5 K.W.
VOLTS ARMATURE
ARMATURE CURRENT
120
100
80
60
40
20
20
40
60
80
100
120
140
160
180

Plate VII

$e = E_0$ = Constant;-Varying Load.



Generator		Motor	
Degree α	Armature Reaction	Degree α	Armature Reaction
2	90 A.T.	6	275 A.T.
4	170 ..	10	430 ..
7	300 ..	11	500 ..
10	430 ..	14	625 ..
11	500 ..	20	890 ..
16	685 ..	24	1060 ..
17	740 ..		
23	990 ..		
28	1220 ..		

Showing M.M.F. Vectors and Armature Reaction

Plate VIII

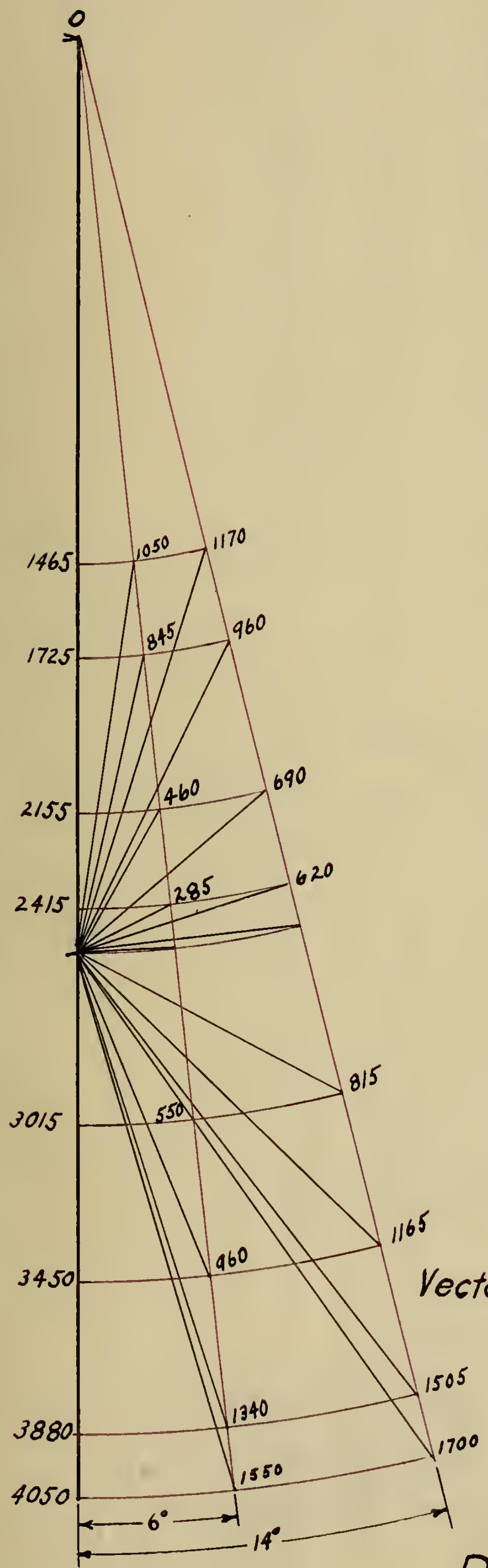
Constant Load— Varying e_1

Small Load.

Degree ∝	Field I	Arm. Reaction
6	.85	1090
"	1.00	845
"	1.25	465
"	1.40	285
"	1.475	260
0	1.475	0
6	1.475	260
"	1.75	550
"	2.00	960
"	2.25	1340
"	2.35	1550

Increased Load

Degree ∝	Field I	Arm Reaction
14	.85	1170
"	1.00	960
"	1.25	690
"	1.475	610
6	1.475	260
0	1.475	170
6	1.475	260
14	1.75	815
"	2.00	1165
"	2.25	1505
"	2.35	1700



Vector Diagram of Magnetomotive Forces and Armature Reactions

Plate IX

Generator Action

I	$\alpha°$	Arm. Rea. Calc.	Arm. Rea. Scaled	Ratio
7.5	0	170	0	
14	2	320	90	.282
25	7	575	300	.52
36	10	825	430	.52
49	17	1120	740	.66
65	23	1490	990	.665
80	28	1830	1220	.667
65	23	1490	990	.665
50	16	1145	685	.598
36	11	825	430	.52
25	7	570	300	.52
16	4	370	170	.46
7.5	0	170	0	

Average = .63

Motor Action

I	$\alpha°$	Arm. Rea. Cal.	Arm Rea. Scaled	Ratio
20	6	460	275	.598
40	11	925	500	.541
47	14	1085	625	.576
60	20	1375	890	.647
80	24	1830	1060	.580
60	20	1375	890	.647
48	14	1100	625	.568
35	10	800	440	.543
20	6	460	275	.598

Average =.59

Table I

Varying Load — $E_o = e = 110$ volts

Showing Field Displacement Factor for Energy Current in Armature.

Degree α	I_{AC}	E_{DC}	I_{DC}	DC. Motor K.W.	A.C. Output	A.C. EI	P.F.
0	7.5	217	8.5	1.85	* 0		
2	14.	216	14.5	3.12	1.22	1.54	.793
7	25	216	20.5	4.32	2.32	2.75	.845
10	36	214	26.5	5.67	3.60	3.96	.910
17	49	212	35.0	7.42	5.17	5.39	.960
23	65	216	45.0	9.72	7.20	7.15	
28	80	215	55.0	11.83	8.96	8.80	
23	65	215	45.0	9.68	7.15	7.15	1.000
16	50	215	35.0	7.53	5.17	5.39	.960
11	36	217	26.5	5.75	3.69	3.96	.930
7	25	218	20.5	4.46	2.32	2.75	.845
4	16	220	14.5	3.19	1.30	1.76	.750
0	7.5	221	8.5	1.87	0		

* No Load losses of machines is 1.85 K.W

Degree α	I_{AC}	E_{DC}	I_{DC}	DC. Gen. K.W.	A.C. Output	A.C. EI	P.F.
0	7.5	221	+8.5	1.87	1.87		
6	20	217	0	0	*1.87	2.2	.85
11	40	206	-9.5	1.96	2.06	4.4	.47
14	47	209	-13.0	2.72	2.86	5.17	.54
20	60	203	-20.0	4.06	4.36	6.60	.66
24	80	202	-25.8	5.22	5.73	8.80	.65
20	60	209	-20.5	4.28	4.59	6.60	.70
14	48	212	-13.0	2.75	3.00	5.28	.57
10	35	216	- 7.0	1.51	1.63	3.85	.42
6	20	217	0	0	1.87	2.20	.85
0	7.5	220	+8.5	-1.87			

* No Load losses of machines is 1.87 K.W.

Table II

Varying Load — $E_o = e = 110$ volts

Calculation of Power Factor in Machine-Varying Load.

Small Load

Angles as Read	I_f	$\alpha°$	Arm. R. Cal.	Arm. R. Scaled	Ratio
72	.85	6	960	1090	1.135
"	1.00	"	735	845	1.115
"	1.25	"	505	465	.92
"	1.40	"	480	285	.514
"	1.475	"	460	260	.556
69	1.475	0	170	0	
72	1.475	6	460	260	.556
"	1.75	"	620	550	.887
"	2.00	"	850	960	1.13
"	2.25	"	1100	1340	1.22
"	2.35	"	1190	1550	1.29

Larger Load

Angle as Read	I_f	$\alpha°$	Arm. R. Cal.	Arm. R. Scaled	Ratio
76	.85	14	1260	1170	.93
"	1.00	"	1100	960	.87
"	1.25	"	1030	690	.67
"	1.475	"	960	610	.636
72	1.475	6	460	260	.556
69	1.475	0	170	0	—
72	1.475	6	460	260	.556
76	1.75	14	1100	815	.74
"	2.00	"	1145	1165	1.02
"	2.25	"	1375	1505	1.10
"	2.35	"	1440	1700	1.18

Table III

Constant Load—Varying e

Field Displacement Factor for Energy Current in Armature